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BALLISTIC INTEGRITY OF STUD WELDS

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FABRICATION AND TECHNOLOGY DEMONSTRATION BRANCH

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MATERIALS TESTING AND EVALUATION BRANCH

June 1988

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ABSTRACT

Stud welds were fabricated in standard and ultrahigh strength armor steels. Bend, torque, tensile impact and ballistic impact tests were performed. Results from arc welded fasteners and stud welded hollow fasteners are compared with those from conventional stud welds. It was determined that the shock waves resulting from direct ballistic impact will cause failure of small welded fasteners regardless of the welding process employed. Factors influencing ballistic performance and methods of minimizing secondary projectile action are also presented.

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INTRODUCTION

Arc stud welding is widely used in industry, manufacturing, and construction.[1,2] It has been previously used on the exterior of armored vehicles but has not been permitted anywhere within vehicle interiors due to the presumed high probability of stud failure and secondary projectile action, presenting a considerable threat to operating personnel.

The probability of stud failure is considered to have been high because of the expected formation of hydrogen induced cracks, which provide initiation sites for rapid crack growth through a brittle layer of untempered martensite in the armor heat affected zone (HAZ).

Typically, there are three conditions which must be simultaneously present to initiate the formation of hydrogen induced cracks. These are: 1) a susceptible microstructure, i.e., martensite; 2) a critical level of diffusable hydrogen, approximately 10 ppm; and 3) a tensile stress, residual or applied. The rapid thermal cycle inherent in the process and the high hardenability of armor steels would suggest that the occurrence of cracks in stud welds is likely. Similar conditions, however, exist during arc welding which is presently used in the installation of appurtenances on armored vehicles.

The purpose of the work presented here is to evaluate methods of minimizing the formation of hydrogen induced cracks, to improve HAZ resistance to brittle crack propagation, to develop improved testing methods, and to develop application guidelines for stud welded fasteners. Potential armored vehicle applications for stud welding include wiring, hydraulic, stowage, and armor installations.

EXPERIMENTAL

Stud welds were fabricated with a Nelson NS-30 stud welding unit and a Westinghouse type WSH constant current power supply. SAE steel fastener grade 5 and 304 stainless steel studs, with threads of 1/2-13 were used. Rolled homogeneous armor (RHA), MIL-A-12560, and ausformed textured steel workpieces were welded. The hardnesses of the 1.125-inch-thick RHA and 2.0-inch-thick textured steel were 33 and 52 HRC, respectively. Chemical compositions of the materials used are shown in Table 1.

Table 1. CHEMICAL COMPOSITION OF WORKPIECE AND STUD MATERIALS

	(Weight Percent)								
	C	Mn	Ni	Cr	Mo	Si	P	S	Cu
MIL-A-12560	0.25	0.26	2.21	1.39	0.24	0.26	0.011	0.007	0.19
Textured Steel	0.40	0.58	5.43	0.11	0.46	1.24	0.006	0.005	0.97
304 Stainless Steel	0.08	2.0	8.0	18.0	-	1.0	0.040	0.030	-
Grade 5 Steel	0.19	0.88	0.03	0.07	0.01	0.21	0.010	0.019	-

1. Welding Handbook, Welding Processes - Arc and Gas Welding and Cutting, Brazing and Soldering, v. 2, 7th Ed., American Welding Society, Miami, Florida, 1978, p. 261-294.
2. Metals Handbook, Welding, Brazing, and Soldering, v. 6, 9th Ed., American Society for Metals, Metals Park, Ohio, 1983, p. 729-738.

The initial series of weld schedules tested were selected based upon a Plackett-Burman experimental design[3] which is capable of statistically evaluating the significance of 6 process variables. The 6 independent variables, each with 2 values, were screened in a series of 12 trials as shown in Table 2. Independent variables and their assigned values are listed in Table 3. Weld time remained constant at 0.5 second for all welds. Current values were within 25 percent of manufacturer's recommendations. Preheat and postheat temperatures were limited to 325°F due to practical application restrictions and the fact that the tempering temperature of the textured steel was 350°F. Base plate surfaces were either as-received mill finish or ground and cleaned with acetone. Welds made on ground surfaces were additionally shielded by an argon filled shroud.

Table 2. TWELVE-RUN PLACKETT-BURMAN DESIGN

	Variable					
Trial	1	2	3	4	5	6
1	+	+	-	+	+	+
2	+	-	+	+	+	-
3	-	+	+	+	-	-
4	+	+	+	-	-	-
5	+	+	-	-	-	+
6	+	-	-	-	+	-
7	-	-	-	+	-	+
8	-	-	+	-	+	+
9	-	+	-	+	+	-
10	+	-	+	+	-	+
11	-	+	+	-	+	+
12	-	-	-	-	-	-

Table 3. VALUES OF FACTORS USED IN PLACKETT-BURMAN SCREENING DESIGN

	(+)	(-)
Stud Material	Grade 5 Steel	304 Stainless Steel
Workpiece	RHA	Textured Steel
Current	1000 A	825 A
Surface Preparation	Ground/Ar Shield	None
Preheat	325°F - 1.5 hr	None
Postheat	325°F - 1.5 hr	None

Screening experiment welds were first inspected by liquid penetrant and then subjected to bend and torque tests and a microhardness survey. Bend tests were performed in accordance with the Structural Welding Code, AWS D1.1. Torque testing was performed on an MTS servo-hydraulic torsion machine at a rate of 100 degrees rotation per minute.

3. PLACKETT, R. L., and BURMAN, J. P. *The Design of Optimum Multifactorial Experiments.* Biometrika, v. 33, 1946, p. 305.

Based on the results of the screening experiments, an optimum set of process parameters were selected and additional welds were fabricated for tensile impact and ballistic testing. The tensile impact tests were performed on a 2200 ft-lb Charpy impact machine. The threaded end of studs was screwed into the back side of the pendulum, Figure 1. The base plate was stopped by an anvil as the specimen was dropped.

Ballistic tests were performed on RHA plates welded with studs spaced a mimimum of six inches apart, Figure 2. Plates were impacted on the side opposite to the stud welds within 0.5 inch of the stud position. A 20-mm proof projectile, at 0° obliquity was used. The velocity of 2950 +/- 25 fps was selected because it resulted in minor bulging only on the back side of monolithic unwelded plates. Welds were tested at room temperature and -40°F in a preloaded and unloaded condition. Preloaded studs were loaded with 20 lbf.

In an attempt to interrupt fracture paths, 5/16" and 1/4" holes were drilled into the ends of a few stainless steel studs. These studs were also stud arc welded and ballistically impacted. For comparison, stainless steel studs were also gas tungsten arc welded (GTAW) to an RHA plate with an ER 304 filler alloy.

RESULTS

All weld schedules tested produced welds of uniform geometry as shown in Figure 3. Visual and liquid penetrant inspection failed to reveal weld defects including hot cracks and hydrogen induced cracks. All welds met bend test requirements. Quantifying bend test results were, however, difficult due to the nature of the test.

Welds were sectioned for metallographic and microhardness evaluations, and no cracks were found. A typical cross section of a weld is shown in Figure 4. Microhardness traverses through typical welds in RHA and textured steel are show in Figures 5 and 6. Although no significant increase in hardness was observed in the HAZ of the textured steel, a dramatic increase in hardness, up to 46 HRC, was observed in the HAZ of the RHA.

A summary of the statistical effect and the minimum significant effect for the maximum torque response of the screening experiment is shown in Table 4. If the absolute value of an effect is greater than the minimum significant effect, then the factor is considered to be significant. Responses with less than the minimum significance either depend only weakly on the dependent variable or are within the experimental scatter. The magnitude and algebraic sign of the effects are important since they determine the confidence level. From Table 4 it can be seen that torque strengths increase with decreasing current and with ferritic (as opposed to austenitic) stud materials. Lower current levels translate to lower heat inputs and, therefore, smaller HAZ sizes. The grade 5 studs failed in the weld at an average maximum torque of 225 ft-lb. The austenitic stainless steel studs failed in the thread area at an average maximum torque of 173 ft-lb.

Table 4. STATISTICAL EFFECT AND MINIMUM SIGNIFICANT EFFECT FOR EACH INDEPENDENT VARIABLE

Stud Material	Workpiece	Current	Surface Preparation	Preheat	Postheat	Minimum Significant Factor Effect*
668	108.3	-296.7	-69	97.3	-96.7	254.9

*95% Confidence Level

The tensile impact values of grade 5 studs welded to the textured steel were low, approximately 136 ft-lb. Tensile impact results for 304 stainless steel studs welded to both RHA and textured steel, with and without preheat, are summarized in Table 5.

Table 5. TENSILE IMPACT VALUES (ft-lb) FOR 304 STAINLESS STEEL STUDS WELDED TO RHA AND TEXTURED STEELS AT VARIOUS PREHEAT TEMPERATURES

Preheat Temperature (°F)	RHA	Textured
70	261	215
225	238	227
325	261	249
450	284	284

The 304 stainless steel studs, with and without preload, tested at room temperature and -40°F, all failed under ballistic impact. Studs adjacent to the point of impact did not fail. Grade 5 studs behaved similarly to the stainless steel studs, except, that in one instance at -40°F, an adjacent preloaded stud failed. However, unloaded studs impacted 1.5 inches from the stud position did not fail at -40°F.

Preloaded studs typically failed in the weld toe on the stud side, Figure 7. All others either completely failed through the HAZ in the armor as in Figure 8, or initiated failure in this region, as in Figure 9. Failed studs were recovered up to 20 feet from the point of impact.

The GTAW studs, Figure 10, and the stud arc-welded hollow/drilled out studs, Figure 11, all failed through the HAZ of the armor when tested at room temperature without preload.

DISCUSSION

Standard tests, i.e., bend and torque, for stud welding process qualification do not provide the necessary data for high strength steel armor applications. This is mainly due to the low strain rates employed and the fact that stresses are concentrated in the stud and not in the HAZ of the armor. The results presented here do, however, confirm that lower HAZ hardness and smaller HAZ size improve tensile impact and torque strength properties, respectively. The most significant result of the parametric study performed was that no hydrogen induced cracks were discovered. This was especially surprising for the textured steel welds since it is normally extremely difficult to successfully weld this material without high preheat temperatures, low hydrogen conditions, and/or austenitic filler alloys.

Since hydrogen induced cracking is not expected to be a major concern, except under severe conditions, the critical factor limiting stud weld integrity must, therefore, be the high hardness and associated low ductility of the HAZ.

HAZ hardness can only be limited by selecting a material with a lower hardenability or by preheating and/or postheating. All armor steels, however, have sufficiently high hardenability such that the presence of martensite in the HAZ of stud welds is virtually guaranteed. Postweld tempering, most likely by induction or Joule heating methods, would lower maximum HAZ hardnesses. However, the process is expensive and difficult to control.

The remaining alternative, therefore, is to interrupt the shape and form of a high hardness HAZ, with tougher unaffected base material, by either conventionally arc welding studs only around their periphery or by arc stud welding hollow ended studs. The use of hollow ended studs still provides the same high process efficiencies as standard stud arc welding but does not result in a continuous HAZ. Larger stud cross-sectional areas would, however, be required for matching fastener strengths.

Even though the hollow ended studs tested here failed in ballistic impact, most likely due to limited stud diameter, the GTAW studs failed in a similar manner. Therefore, the possibility of secondary projectile action not only exists with stud welded attachments, but also with arc welded attachments.

Recognizing that any welded fastener to armor steel can fail under direct ballistic impact, fasteners and their locations should be designed such that the failure of any individual weld will not result in any injury to operating personnel. Fastener loading, spacing, and probability of impact must all be considered.

The use of spall liners incorporating pockets for flanged studs is one possible alternative which would minimize the threat of secondary projectile action. More work, however, is required.

CONCLUSIONS

Stud welds in ultrahigh strength armor steels can be fabricated without hydrogen-induced cracks.

Standard mechanical tests for stud weld process qualification should be complemented by tensile impact and ballistic impact tests for stud weld applications in the interior of armored vehicles.

Shock waves from direct ballistic impact will result in the failure of stud welds. Weld failure can be attributed to the formation of martensite in the heat-affected zone and the concentration of stress at the toe of welds.

Interruption of the brittle martensitic layer in heat affected zones, through the use of hollow ended fasteners, did not improve ballistic performance.

Arc welded fasteners similarly failed under ballistic impact.

The degree of lateral damage resulting from ballistic impact depends on several factors including ambient temperature, loading, and stud design and location.

The use of flanged studs in applications incorporating spall liners is proposed.

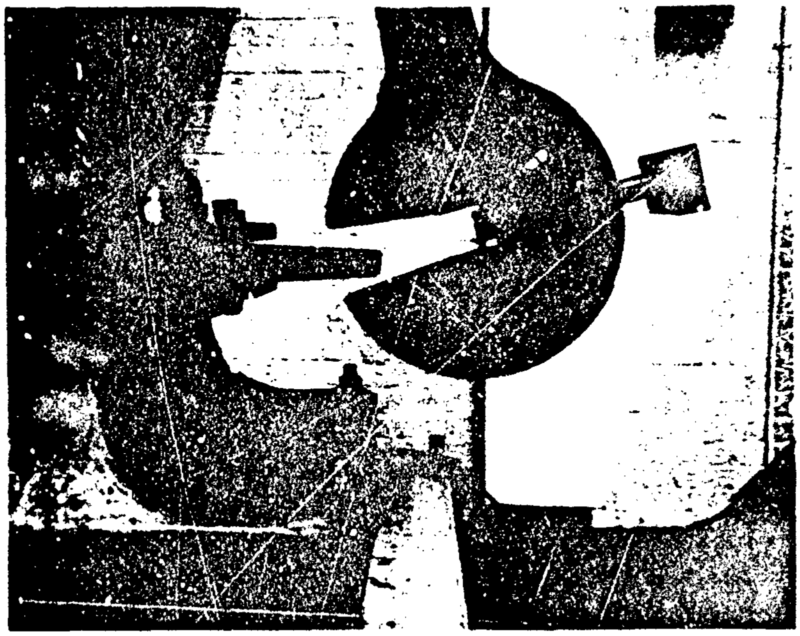

Figure 1. Setup for tensile impact testing.

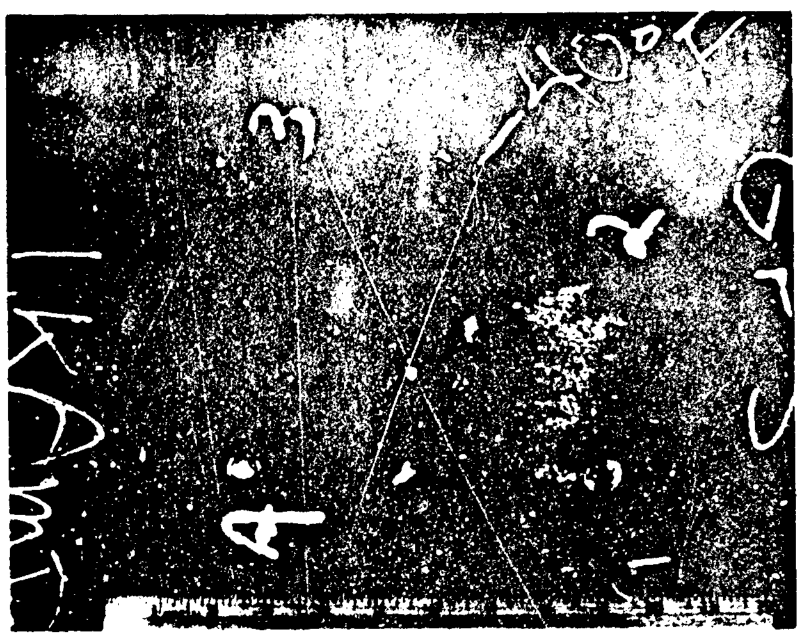

Figure 2. Typical stud welded plate used in ballistic testing.

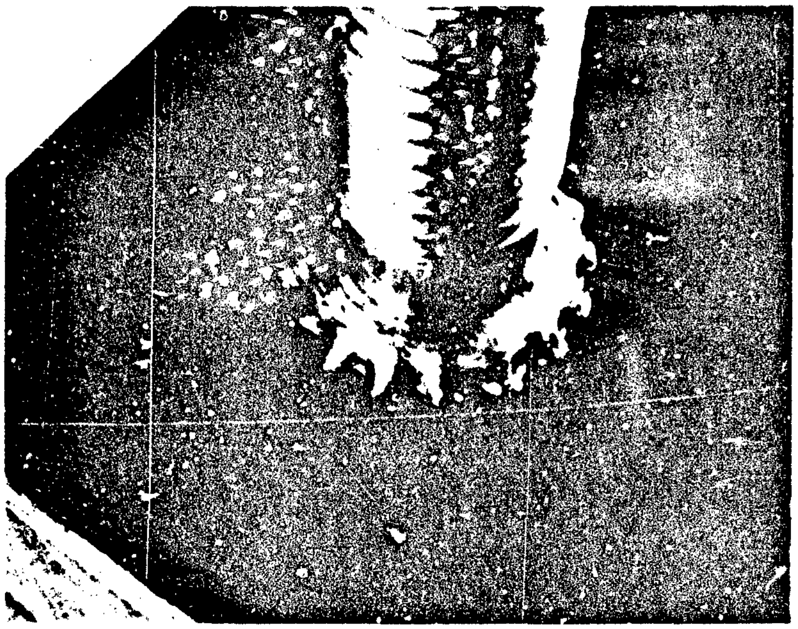

Figure 3. Photograph of a typical stud weld.

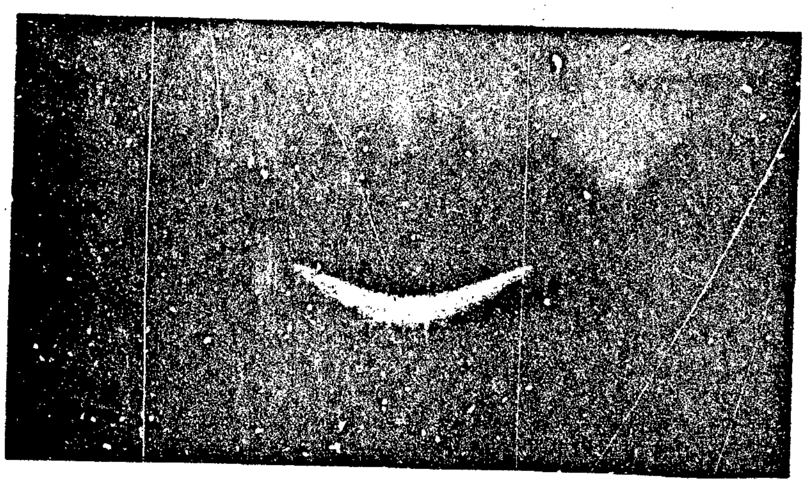

Figure 4. Typical cross section of a stud weld.

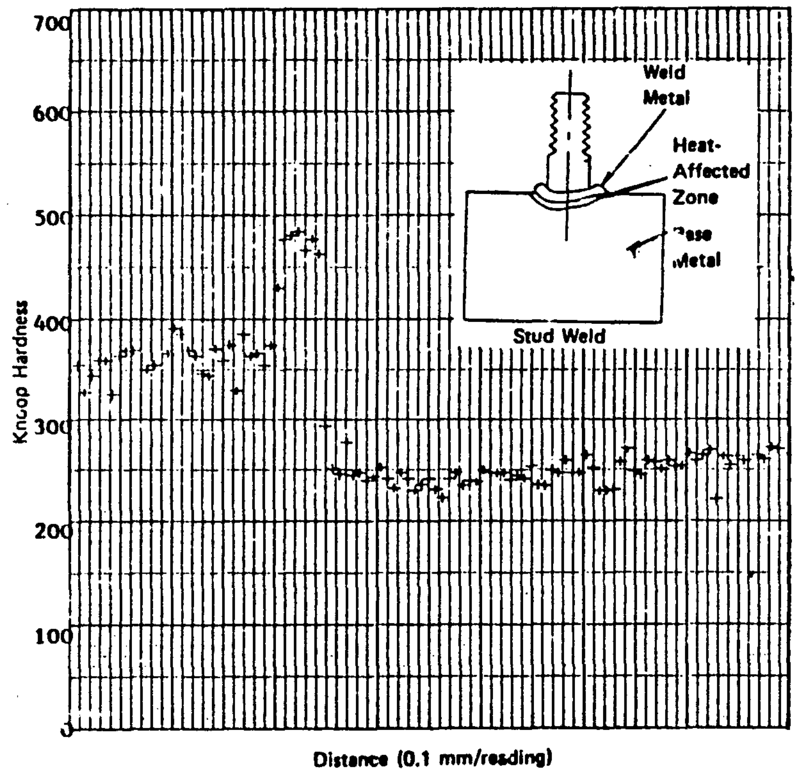

Figure 5. Microhardness traverse through RHA base material into a 304 stainless steel stud.

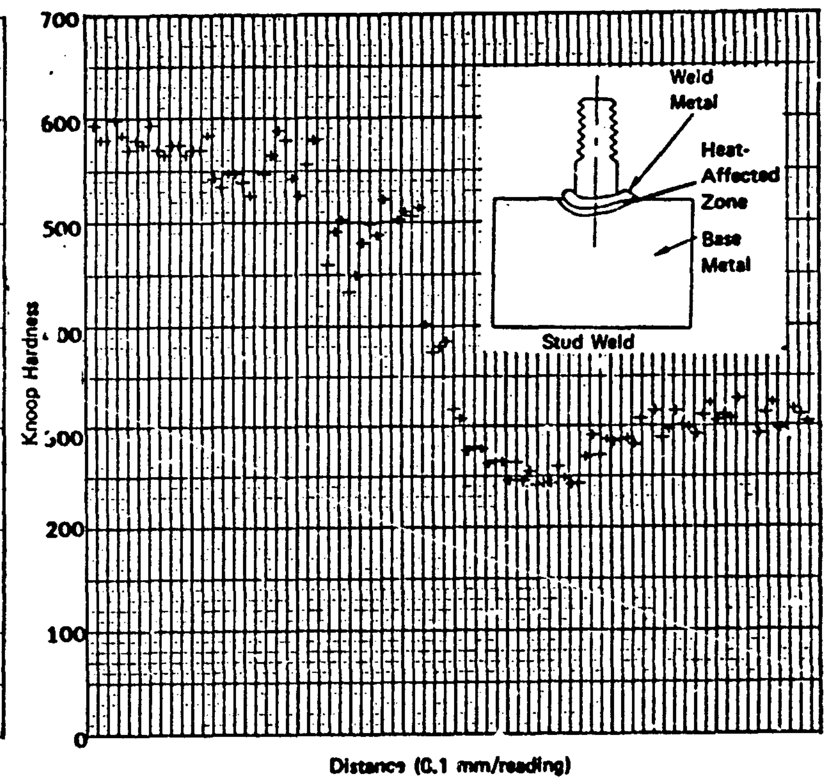

Figure 6. Microhardness traverse through textured steel base material into a grade 5 stud.

Figure 7. Failure of a ballistically impacted stud weld through the weld toe on the stud side of the joint.

Figure 8. Failure of a ballistically impacted stud weld through the heat affected zone of the armor.

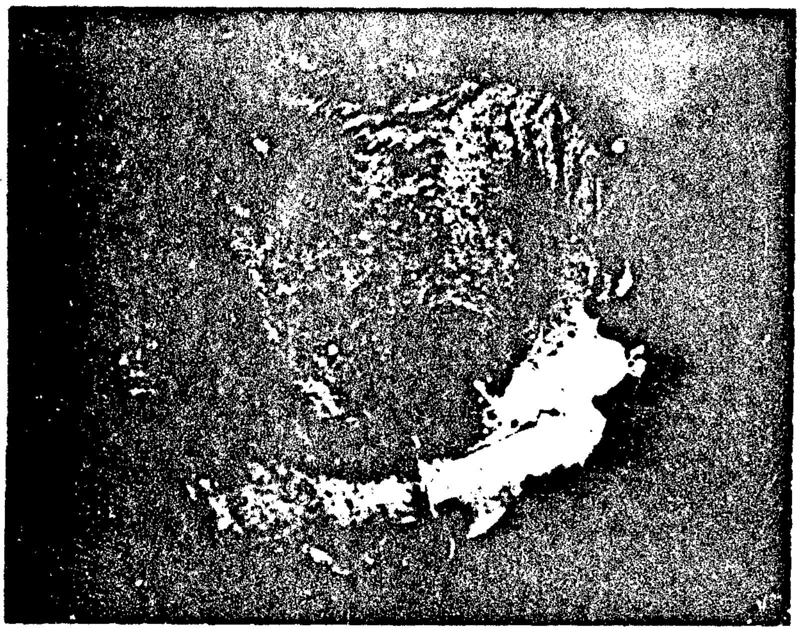

Figure 9. Failure of a ballistically impacted stud which initiated in the heat affected zone of the armor and propagated through the weld metal.

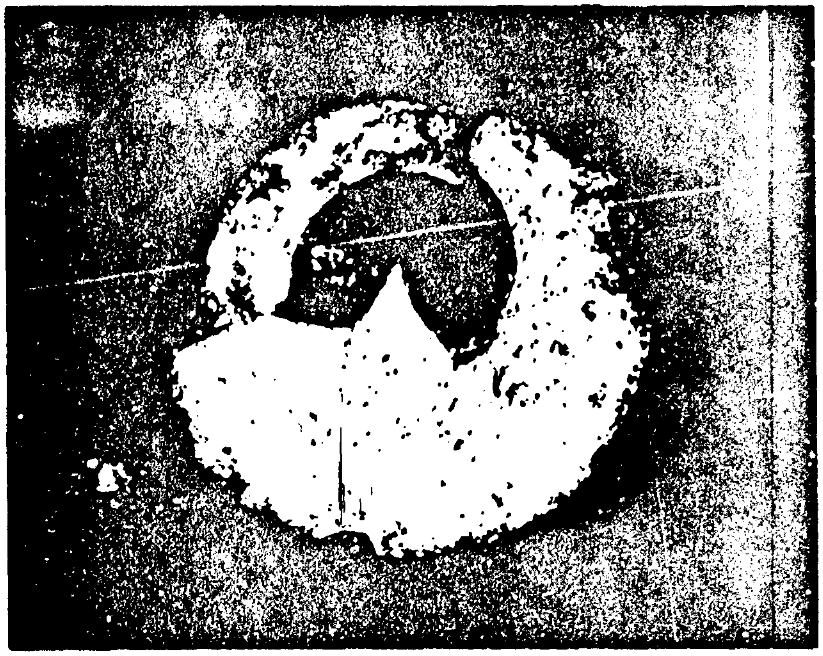

Figure 10. Fracture surface of a gas tungsten arc welded stud.

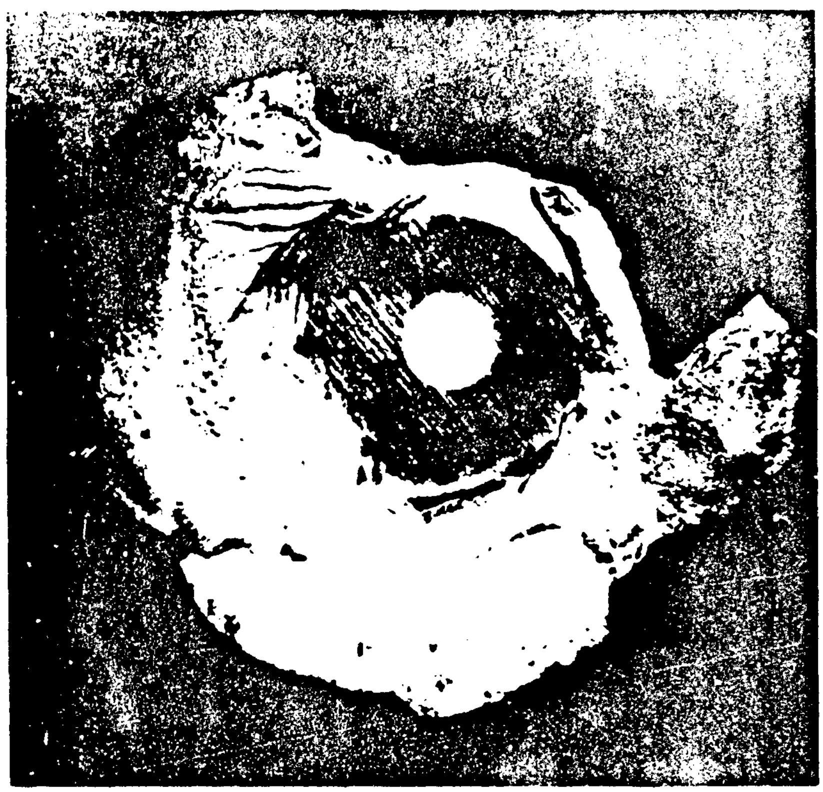

Figure 11. Fracture surface of a hollow stud arc welded fastener.

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Stud welds were fabricated in standard and ultrahigh strength armor steels. Bend, torque, tensile impact and ballistic impact tests were performed. Results from arc welded fasteners and stud-welded hollow fasteners are compared with those from conventional stud welds. It was determined that the shock waves resulting from direct ballistic impact will cause failure of small welded fasteners regardless of the welding process employed. Factors influencing ballistic performance and methods of minimizing secondary projectile action are also presented.

U.S. Army Materials Technology Laboratory,
Watertown, Massachusetts 02172-0001
BALLISTIC INTEGRITY OF STUD WELDS
William S. Ricci, James E. Catalano,
Attilio Santoro, and William L. Crenshaw

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